

Article

Design-Driven Exposure Architectures in Urban Parks: How Space, Behavior and Perception Concentrate Particulate Matter Doses

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Abstract

Urban parks are widely regarded as healthy and sustainable urban infrastructures, yet their respiratory benefits depend on the coupling of design, behaviour, and perception rather than ambient PM concentrations alone. A multi-season daytime fair-weather panel study across five urban park space types integrated in situ PM monitoring, SOPARC-based behavior mapping (9173 users), dwell-time surveys, and inhalation-rate libraries to estimate per capita inhaled doses, while an on-site survey ($n = 837$) assessed perceived PM and its influence on space choice. Understory and water spaces exhibited the highest PM₁₀ and TSP concentrations, whereas waterfront areas were the cleanest; winter concentrations were elevated but preserved the same space-type ranking. Sports spaces had the most intense activity profiles (61.9% moderate-to-extreme), and understory and sports spaces supported the longest stays, with little seasonal change in either intensity or duration. Consequently, per capita PM exposure was highest in sports and understory spaces and lowest in water and waterfront spaces. Spaces that attracted more users also delivered higher per capita doses, indicating an overlap between popularity and high-dose micro-environments. Perceptually, 94.9% of users rated PM as low or relatively low in water spaces, whereas squares had the highest share of “moderate or worse” ratings (26.4%); 78.1% chose locations based on perceived air quality, despite weak or even negative correlations with measured PM. These findings reveal a design-driven exposure architecture in which space configuration organizes both PM concentrations and user behavior, while misperception can steer visitors, especially in winter, toward the very park micro-environments that deliver the highest inhaled doses. This study provides evidence for exposure-aware park design and management that can reduce respiratory risk while supporting sustainable outdoor recreation and healthier urban living.



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1. Introduction

Airborne particulate matter (PM), especially fine particles, remains one of the largest environmental causes of premature mortality worldwide. Recent estimates suggest that

ambient PM_{2.5} contributes to more than four million premature deaths annually, primarily through cardiovascular and respiratory pathways, with the heaviest burdens in low- and middle-income countries in Asia and Africa [1–3]. Because most exposure occurs where people live, move, and recreate, the micro-environments of everyday life (streets, homes, workplaces, and public open spaces) have become central to contemporary exposure science [4].

Urban green spaces are increasingly promoted as “nature-based prescriptions” to mitigate environmental risks and enhance physical and mental health [5,6]. Parks in particular are key sites where residents are expected to gain simultaneous benefits: cleaner air compared with traffic corridors, opportunities for moderate-to-vigorous physical activity (MVPA), and psychological restoration. Yet evidence on the air-quality dimension of parks is decidedly mixed. Fine-scale monitoring shows that trees, shrubs, and open water can sometimes reduce particle concentrations through deposition and enhanced dispersion, but they can also collect pollutants in poorly ventilated canopies or channel traffic emissions into adjacent green spaces [7–9]. As a result, not all park spaces are equally “clean”, and some ostensibly attractive micro-environments may actually deliver relatively high PM concentrations.

At the same time, the way parks are designed strongly structures when, where, and how intensively people use them. Multi-city studies show that built-environment attributes such as connectivity, density, and land-use mix can explain large differences in population physical activity [10,11]. Within parks, specific facilities and spatial layouts e.g., trails, sports fields, plazas, shaded seating, and waterfronts, govern the distribution of users and their activity intensity more than simple metrics such as park size or distance alone [12,13]. In other words, park design does not only provide “opportunities” for health-enhancing behaviors; it also configures who spends time where, for how long, and how strenuously.

From an exposure-science perspective, these patterns are critical because dose is determined by more than ambient concentration. Inhaled dose depends on the product of concentration, respiratory rate (linked to activity intensity), and time spent in a given micro-environment [4,14]. Research on active travel has shown that the health benefits of walking and cycling generally outweigh the risks from increased inhalation of polluted air, but only because the same design that elevates exposure also delivers substantial gains in physical activity [15,16]. By analogy, the health implications of time spent in urban parks cannot be inferred from PM concentrations alone; they depend on how park design, user behavior, and air quality interact to organize doses rather than just levels.

A further complication is that people rarely choose park locations based on measured concentrations. Instead, they rely on perceived air quality and other sensory cues. Social-science research has documented substantial mismatches between measured pollution and perceived air quality, shaped by local context, media narratives, and social inequalities [17–19]. For example, residents in heavily polluted cities may underestimate local air risks or anchor their perceptions more on smog episodes and media coverage than on everyday PM exposure [17,20]. When such perceptual biases guide micro-scale choices in parks, they can produce maladaptive behavior, for example, crowding into “clean-looking” waterfronts or shaded tree canopies that are in fact among the most polluted micro-environments.

Despite these advances, empirical evidence linking park micro-environments, measured PM, observed behavior, and perceived air quality within a single framework remains limited. Most studies either map concentrations across parks without systematically observing user behavior or they examine park-based physical activity and visitation without integrating concurrent pollution measurements [7,21]. Few investigations quantify how different space types (e.g., tree-understory areas, hard-surfaced squares, sports facilities)

jointly shape concentration, activity intensity, and dwell time across seasons. Even fewer evaluate whether users' perceptions of air quality are systematically aligned or misaligned with the micro-environments that deliver the highest per capita doses.

This study addresses these gaps using a multi-season, multi-park observational design in a northwestern Chinese city. We classified typical urban park spaces into five design-informed types (e.g., understory, waterfront, water, square, and sports fields) and monitored PM_1 , $PM_{2.5}$, PM_{10} and total suspended particles (TSP) alongside microclimate, observed behavior (type, intensity, and user counts), and perceived air quality across four seasons. Building on exposure science and urban design theory, this study aims to determine how park space design influences three key determinants of respiratory exposure to PM: PM concentrations, user behavior, and users' perceptions of air quality. By integrating these pathways, we further assess how spatial design ultimately shapes PM exposure in urban parks. Specifically, we ask:

- (1) How do PM concentrations and inferred inhaled doses vary among park space types and across seasons?
- (2) Do the spaces that attract the most users and longest dwell times also deliver the highest per capita PM doses, and how is this pattern modulated by seasonal changes in background pollution?
- (3) To what extent do park users' perceptions of air quality align with measured PM levels in different space types, and do these perceptions steer users toward or away from high-dose micro-environments?

Across these questions, we advance the notion of a design-driven exposure architecture in urban parks. By reframing park air quality from "how clean is the air?" to "who receives which doses, where, and why?", this work provides a basis for rethinking park design guidelines in cities where particulate pollution remains a chronic health burden. The findings contribute to the development of healthier and more sustainable urban parks by identifying design strategies that reduce PM exposure while supporting outdoor recreation and park use.

2. Materials and Methods

2.1. Study Area

Xianyang is one of China's key cities for air-quality surveillance, characterized by a temperate continental monsoon climate and frequent winter haze episodes driven by regional emissions and unfavorable dispersion conditions. Within the built-up area, four large urban parks that provide regular public recreational services were selected as study sites. These parks were chosen to represent typical neighborhood- to district-scale urban parks in Xianyang. All four parks were located away from major industrial point sources and primary arterial roads and exhibited broadly comparable surrounding environmental conditions (Figure 1).

Within these parks, ten fixed observation plots were established to capture the micro-environmental diversity of park spaces. Based on spatial function and environmental structure, plots were classified into five archetypal space types, with two replicate plots for each type: (1) square, (2) sports space, (3) understory space, (4) waterfront space, and (5) water space. Detailed selection criteria for each space type, together with information on plot characteristics and surrounding environmental conditions, are provided in Supplementary Text S1 and Table S1. Each plot was mapped in detail prior to data collection, including surrounding tree canopy, shrub belts, water surfaces, and hardscape, to support subsequent interpretation of exposure patterns.

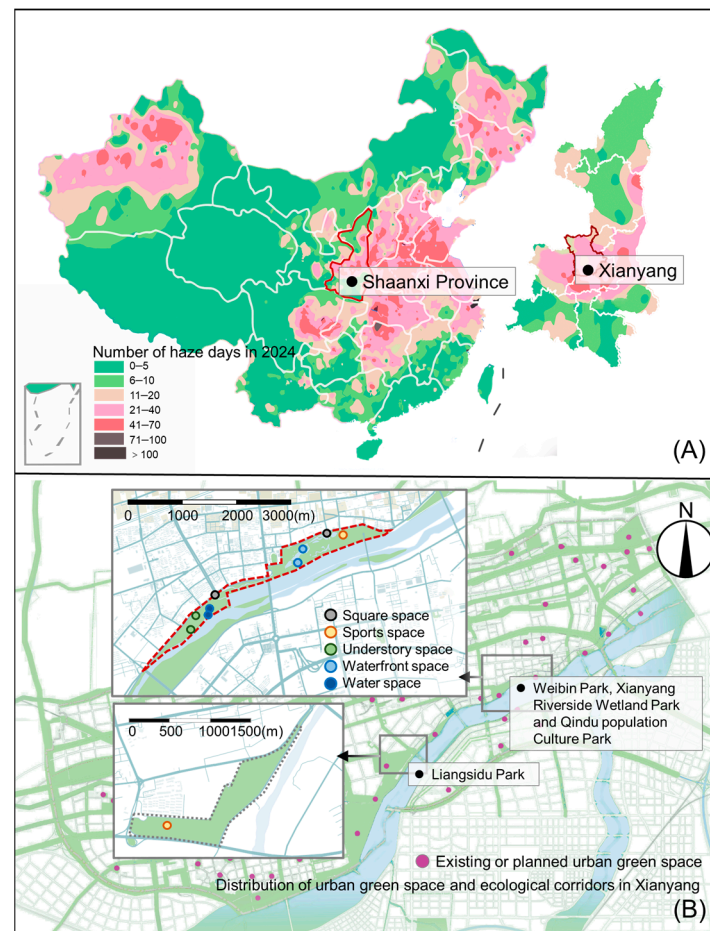


Figure 1. Study area. (A) The situation of PM pollution in the study area in 2024 (measured by the number of smoggy days). (B) Detailed map of the research area and plot distribution.

2.2. Study Design and Sampling Frame

Field campaigns were conducted across four seasons under daytime fair-weather conditions suitable for outdoor recreational activities. Within each season, monitoring was performed on 4 non-consecutive fair-weather days, covering both weekdays and weekends to reflect typical park use. On each monitoring day, all ten plots were measured repeatedly following a fixed rotation schedule so that each plot was sampled in the same set of daytime periods. A “plot-time window” was defined as one complete sampling episode at a given plot during a pre-specified time interval (08:00–10:00, 13:00–15:00, 17:00–19:00). Across all seasons and parks, this design yielded 480 plot-time observations. This panel structure ensured that each space type was observed repeatedly under different seasonal backgrounds while maintaining comparable time-of-day coverage.

Concurrent meteorological parameters, including air temperature, relative humidity, wind speed, and wind direction, were recorded using a portable weather meter (Kestrel 5500, Nielsen-Kellerman, Boothwyn, PA, USA) positioned near the PM sampling inlet at each plot (Table S2). Sampling days were selected to reflect typical daytime fair-weather recreational conditions within each season; nighttime, post-rainfall, strong-wind, and severe-pollution conditions were not included.

2.3. Particulate Matter Monitoring

At each plot, PM_1 , $PM_{2.5}$, PM_{10} and total suspended particles (TSP) were monitored at adult breathing height (1.5 m above ground). Measurements were obtained using a AEROCET 831 Handheld Aerosol Mass Monitor (Met One Instruments, Inc., Grants

Pass, OR, USA), which had been factory-calibrated and cross-checked against a reference instrument operated by the local environmental monitoring station prior to the campaigns. The instruments provided real-time mass concentrations ($\mu\text{g}\cdot\text{m}^{-3}$) for the four particle size fractions based on light scattering. Instruments were sheltered from direct solar radiation while maintaining free airflow around the inlet. Repeated measurements were conducted at four selected points within each plot, and the mean value was used to represent the PM concentration of the space.

2.4. User Behavior and Population Distribution

User presence and activity patterns within each plot were recorded using the System for Observing Play and Recreation in Communities (SOPARC) protocol, which has demonstrated good reliability for park-based physical activity surveillance (McKenzie et al., 2006 [22]; Evenson et al., 2016 [23]). During each observation, every individual was coded by sex and activity intensity, following standard SOPARC decision rules. Inter-observer agreement was assessed prior to formal data collection by having multiple observers simultaneously code the same plots; the results met the requirements for consistency (Table S3). For each plot-time window, we derived: (1) the total number of users present, (2) the distribution of users across activity intensity categories, and (3) the implied behavioral portfolio of the space (i.e., the proportion of time and users engaged in sedentary vs. moderate-vigorous activities). Activity duration for each activity was obtained from the on-site questionnaire survey. These metrics were later linked to the PM panel to estimate activity-specific inhalation doses.

2.5. Exposure Estimation

The degree of exposure was characterized as the per capita PM inhaled dose in each space. Per capita dose was estimated by integrating measured PM concentration, activity-specific inhalation rates, activity composition, and survey-derived dwell time, following exposure assessment practice [14]. For a given space type s and time window t , the average per capita dose $D_{s,t}$ (μg per person per window) for a given particle size fraction was calculated as:

$$D_{s,t} = C_{s,t} \times \Delta t \times \sum_k \left(IR_k \times \frac{N_{k,s,t}}{N_{s,t}} \right)$$

where $C_{s,t}$ ($\mu\text{g}\cdot\text{m}^{-3}$) is the mean PM concentration measured during window t in space s ; Δt (min) is the duration of the observation window; IR_k ($\text{m}^3\cdot\text{min}^{-1}$) is the inhalation rate associated with activity-intensity category k ; $N_{k,s,t}$ is the number of users observed in category k ; and $N_{s,t} = \sum_k N_{k,s,t}$ is the total number of users in that space-time combination.

Activity categories were mapped to inhalation rates based on the compendium [24,25]. Table 1 summarizes the typical observed activities in each intensity tier and the corresponding respiratory volumes used in the calculations. This formulation explicitly incorporates both the environmental term (concentration), driven largely by background pollution and local dispersion, and the behavioral term (activity-weighted inhalation), which is shaped by space design and use.

2.6. Perception Survey

To capture users' perceptions of air quality within the same micro-environments, we conducted synchronized on-site perception surveys during the monitoring campaigns. Immediately after each SOPARC observation at a plot, interviewers approached park users who had spent at least 5 min within the plot domain and invited them to participate in a brief questionnaire. The questionnaire comprised three modules: (1) perceived PM level at the current location on a 5-point Likert scale (from "very clean" to "very polluted");

(2) behavioral intentions, including whether the respondent would change location within the park if they felt the air was polluted; and (3) an open-ended item asking respondents to briefly explain the cues they used when judging local air quality. Open-ended responses were coded into dominant cue categories by two researchers, and disagreements were resolved through discussion. A stratified convenience sampling strategy was employed to balance respondent age and sex across seasons and space types.

Table 1. Intensity categories of typical observed activity and their respiratory volume recommendations.

Activity Intensity	Type of Activity	Recommended Respiratory Rate for Male (L/min)	Recommended Respiratory Rate for Female (L/min)
Static behavior	Lying	6.3	5.1
	Sitting rest	7.5	6.1
Light intensity activity	Standing, chatting while sitting, chatting while standing, sitting combined with standing, playing musical instruments, singing while standing, performing opera, sitting and playing cards, playing cards or chess while sitting, standing for photos, sitting and flying a kite, playing with children	9.4	7.6
Moderate-intensity activity	Walking, playing table tennis, playing tai chi, dancing in the square, ballroom dancing, fishing, children playing, using fitness equipment (light), aerobics (slowly)	25	20.4
Severe intensity activity	Playing basketball, playing badminton, using fitness equipment (intense), aerobics (fast-paced)	37.6	30.6
Extreme intensity activity	Playing soccer, jumping rope	62.6	51

2.7. Statistical Analysis

Analyses focused on three linked questions: (1) how PM concentrations, user behavior, and per capita exposure vary across space types and seasons; (2) how per capita exposure relates to concurrent user numbers; and (3) how perceived PM levels align with measured concentrations.

To examine spatial–seasonal differences, stratified non-parametric comparisons were conducted. Because concentration, behavior, and exposure data exhibited non-normal and heteroscedastic distributions, Kruskal–Wallis tests were applied within seasonally stratified datasets as well as the pooled multi-season dataset, followed by Dunn’s post hoc tests for pairwise contrasts. Resulting *p*-values were corrected for multiple testing using the Benjamini–Hochberg FDR procedure ($q < 0.05$ considered significant). Spearman’s rank correlations were calculated to estimate the bivariate associations between (i) instantaneous per capita exposure and concurrent user numbers and (ii) perceived PM scores and measured concentrations. Open-ended responses on perceptual cues were summarized by coded cue categories and reported descriptively.

To assess the robustness of these primary findings against microclimatic variation and the repeated-measures structure of the data, supplementary mixed-effects sensitivity analyses were performed. For spatial–seasonal differences, Linear Mixed-Effects Models were fitted using log-transformed PM concentration as outcomes. Space type and season were included as fixed effects; temperature, humidity, and wind speed were added as meteorological adjustments; and random intercepts were specified for plot and monitoring day. As a sensitivity analysis, we further examined the association between particulate matter per capita exposure and population size using log-transformed fixed-effects ordinary least squares regression with cluster-robust standard errors. All analyses were conducted in R (version 4.2.0; R Foundation for Statistical Computing, Vienna, Austria).

3. Results

3.1. Spatiotemporal Heterogeneity of PM Concentration

Across the four seasonal fair-weather campaigns, PM₁₀ and TSP concentrations were consistently lowest at waterfront edges and highest in understory and water spaces, with winter levels markedly exceeding those in other seasons (Figure 2, Tables S4 and S5). Significant spatial heterogeneity was observed across the five space types for most particle size fractions, with the exception of PM_{2.5} (FDR-adjusted $q < 0.05$). For PM₁₀ and TSP, concentrations followed a stable ranking: waterfront < squares/sports < water < understory. Waterfront areas maintained the cleanest air across seasons, whereas understory spaces exhibited the most polluted conditions.

Patterns for PM_{2.5} broadly mirrored those of PM₁₀ and TSP, although PM_{2.5} concentrations in understory spaces were slightly lower than those in water spaces. Seasonal variation was pronounced ($p < 0.01$), with winter showing the highest PM levels across all particle sizes (Figure 3). Despite these seasonal shifts in absolute concentration, the relative ordering of space types remained broadly stable, suggesting that spatial design and vegetation structure locked in a persistent concentration hierarchy that was only vertically shifted by seasonal background pollution.

Overall, for most particle-size fractions and seasons, waterfront spaces provided the lowest PM concentrations, whereas understory and water spaces consistently represented the most polluted micro-environments. The robustness of this spatial hierarchy was confirmed by the sensitivity analysis using Linear Mixed-Effects Models (Tables S6–S9). Although meteorological conditions are important determinants of PM concentrations, they were not the primary focus of this study. We analyzed their relevant effects and reported the results in Table S10.

3.2. Spatiotemporal Heterogeneity of Park Users' Behavior

Park design strongly organized behavioral portfolios: sports spaces concentrated the most vigorous activity, whereas waterfront and understory spaces were dominated by sedentary or light-to-moderate intensity behaviors (Figure 4; Table S11). In sports spaces, 61.90% of users engaged in moderate-to-extreme intensity activities, primarily basketball and table tennis. By contrast, understory spaces were overwhelmingly used for moderate or lower-intensity activities (99.48%), such as standing, sitting, or using the fitness equipment lightly. Waterfront areas showed the highest proportion of fully static behavior (48.39%), with sitting and resting as the most common activities.

These patterns were highly stable across seasons. The proportions of activity intensities and the ranking of typical activities within each space type remained nearly unchanged from spring to winter (Figure 4), indicating that spatial configuration, rather than seasonal weather, primarily shaped behavioral intensity profiles. Squares supported a mixed portfo-

lio of walking, sitting, and socializing, whereas water spaces were used mainly for short, moderate or light-intensity activities such as walking, standing or fishing.

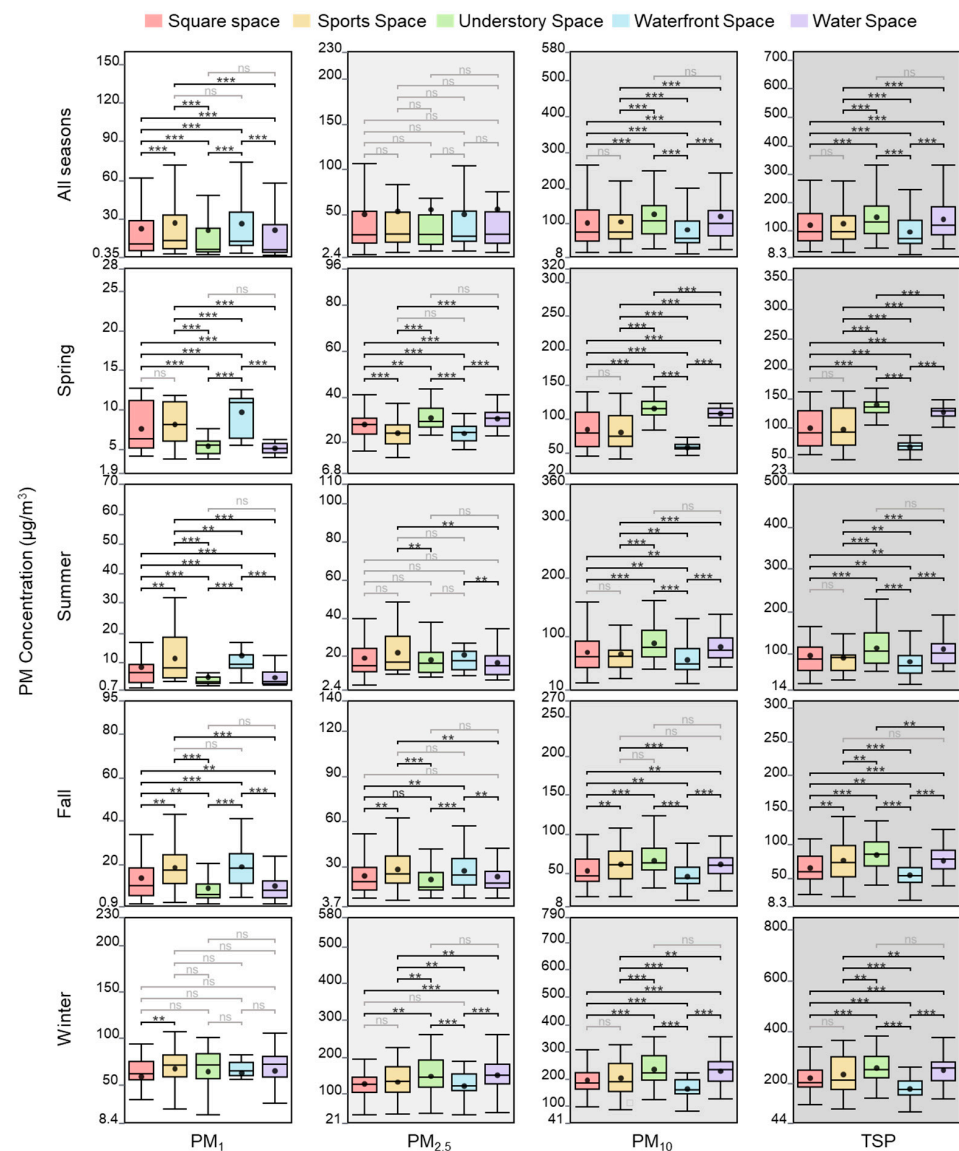


Figure 2. Spatial Variations in PM Concentrations. Significance levels: ns, not significant; $p < 0.01$ (**); and $p < 0.001$ (***). The significance levels in the figure were FDR-corrected, with FDR-corrected q-values < 0.05 .

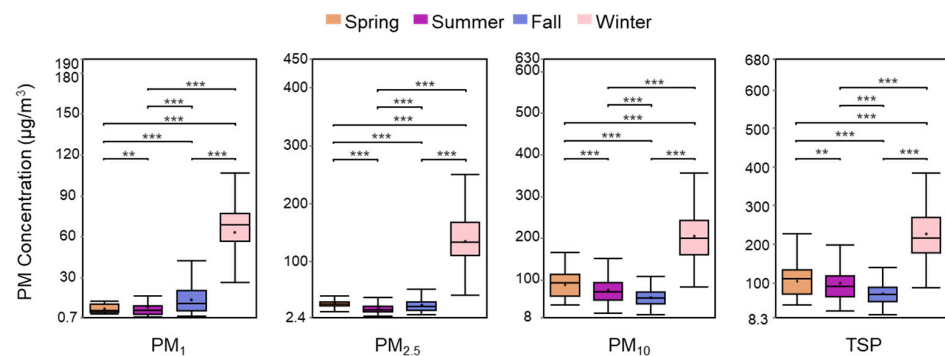


Figure 3. Seasonal Variations in PM Concentrations. Significance levels: $p < 0.01$ (**), and $p < 0.001$ (***). The significance levels in the figure were FDR-corrected, with FDR-corrected q-values < 0.05 .

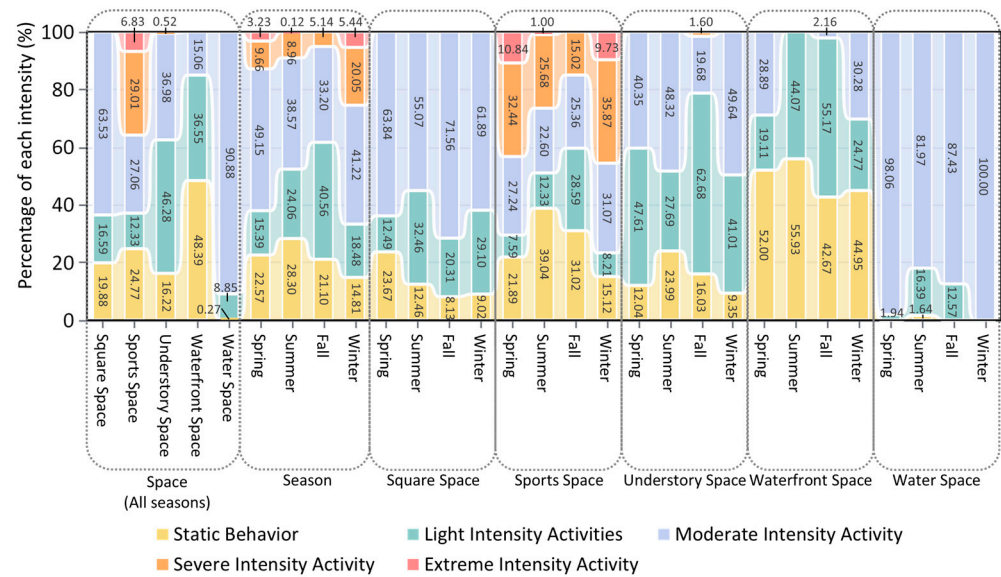


Figure 4. Proportion of activity-intensity categories by space type and season.

Activity duration also varied significantly among space types (Figure 5). The longest stays occurred in sports spaces, followed by understory spaces, squares, waterfront spaces, and water spaces. This pattern indicates that spaces inviting vigorous activity (sports spaces) or comfortable lingering (understory spaces) kept users in place for longer periods. Seasonal differences in dwell time were not statistically significant ($p = 0.20$), again suggesting that design-locked use patterns were stable across the four seasonal campaigns.

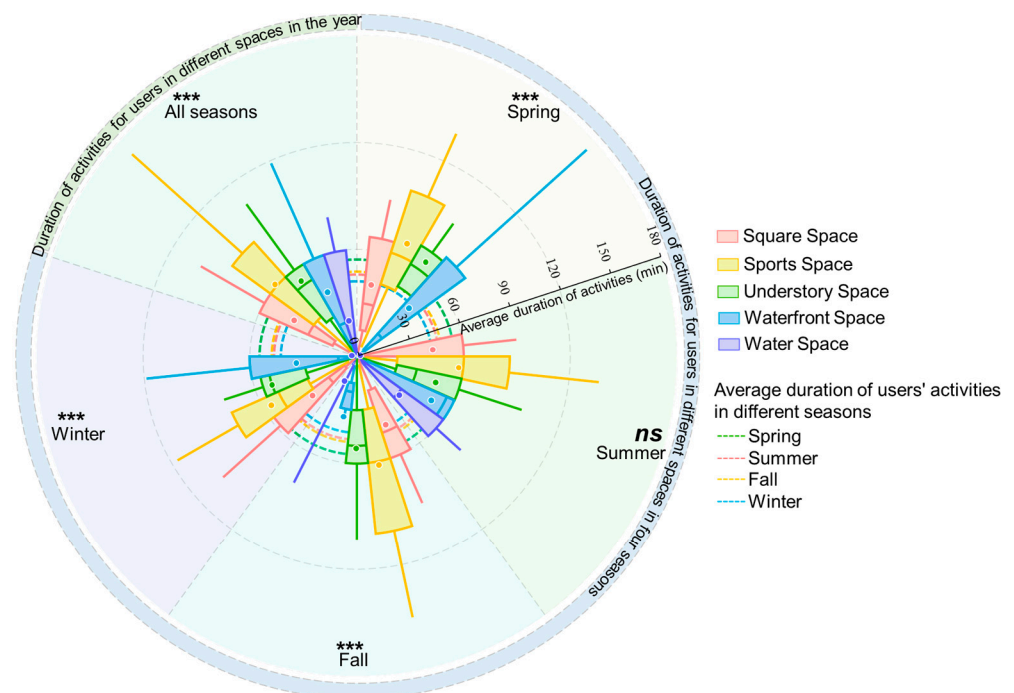


Figure 5. Activity duration by season and space. Significance levels: ns, not significant; $p < 0.001$ (***)

Taken together, these results show that design attributes of park spaces organized both the intensity and duration of behavior in a way that is robust to seasonal change, thereby shaping the behavioral term of inhaled dose.

3.3. Spatiotemporal Heterogeneity of Per Capita PM Exposure

When concentration was combined with activity-weighted inhalation, sports and understory spaces emerged as the highest per capita PM exposure environments across all particle sizes (Figure 6). Multi-season mean per capita doses for PM_{2.5}, PM₁₀, and TSP followed a consistent ranking from lowest to highest: water spaces < waterfront spaces < squares < understory spaces < sports spaces (Table S12). The robustness of this spatial hierarchy was further supported by sensitivity analyses using Linear Mixed-Effects Models (Table S13). The most extreme exposure conditions occurred in sports spaces during winter, where elevated ambient PM concentrations coincided with high-intensity activities and long dwell times. Understory spaces in winter produced the second-highest doses, driven by high concentrations and prolonged (though mostly moderate-intensity) stays. Although absolute exposure varied seasonally (peaking in winter and dropping in spring and summer), the relative ordering of space types remained stable, mirroring the behavioral patterns described above.

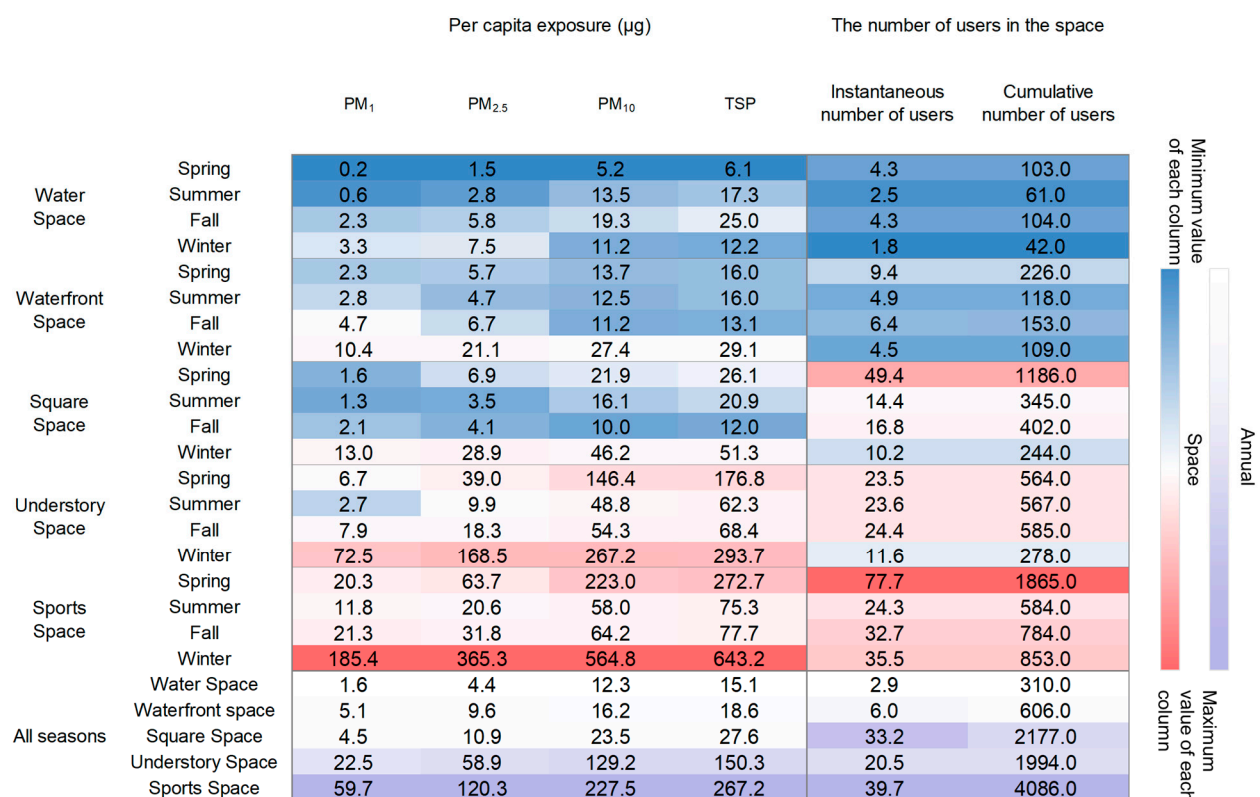


Figure 6. Relationship between instantaneous user numbers and per capita PM exposure by space type and season.

From a dose perspective, these findings indicate that the spatial design of parks does not merely redistribute concentration; it organizes a “dose architecture” in which certain spaces systematically deliver higher per capita inhaled doses under the observed seasonal fair-weather conditions. Sports courts and tree-understory pockets, in particular, function as dose hotspots within the park system. To complement the per capita view, we also considered the population-weighted exposure conceptually, defined as the per capita dose multiplied by concurrent user numbers. Given that sports and understory spaces simultaneously exhibited the highest per capita doses and comparatively large user counts, they are likely to be major contributors to population-level park PM exposure in the observed setting.

3.4. Relationship Between Per Capita Exposure and User Distribution

Across the four seasonal fair-weather campaigns, observations showed that the most popular spaces were also the highest-dose spaces. On average, sports spaces attracted the largest number of users (39.7 per observation window), followed by squares (33.2), understory spaces (20.5), waterfront spaces (6.0), and water spaces (2.9). With the exception of understory areas, which peaked in autumn, most space types reached maximum usage in spring, consistent with seasonal preferences for outdoor activity (Figure 6). Across all seasons and particle sizes, per capita PM exposure was significantly and positively associated with concurrent user numbers (Table 2). Multi-season Spearman correlation coefficients ranged from $\rho = 0.52$ to 0.59 (all $p < 0.01$), increasing to $\rho = 0.68$ – 0.71 in winter. This positive association persisted in the sensitivity analysis (Table S14). This implies that the more crowded a space was, the higher the per capita PM dose it tended to deliver, particularly under high-background winter conditions. This pattern was robust across PM_1 , $PM_{2.5}$, PM_{10} and TSP, underscoring that design-driven crowding and behavioral intensity amplify individual risk precisely where the most people are exposed. Combining these correlations with the dose rankings in Section 3.3 suggests that sports and understory spaces act as structural “dose hubs” in the park exposure network, where high ambient concentrations, high inhalation rates, long stays, and high user density converge.

Table 2. Correlation between per capita PM exposure and user numbers across seasons.

		Overall	Spring	Summer	Fall	Winter
PM_1	p	<0.01	<0.01	<0.01	<0.01	<0.01
	ρ	0.521	0.591	0.630	0.558	0.702
	95% CI	[0.453, 0.584]	[0.461, 0.697]	[0.508, 0.727]	[0.421, 0.670]	[0.598, 0.783]
$PM_{2.5}$	p	<0.01	<0.01	<0.01	<0.01	<0.01
	ρ	0.564	0.559	0.679	0.594	0.68
	95% CI	[0.500, 0.622]	[0.422, 0.671]	[0.570, 0.765]	[0.464, 0.699]	[0.570, 0.766]
PM_{10}	p	<0.01	<0.01	<0.01	<0.01	<0.01
	ρ	0.59	0.539	0.660	0.598	0.704
	95% CI	[0.528, 0.645]	[0.396, 0.654]	[0.546, 0.751]	[0.469, 0.702]	[0.601, 0.784]
TSP	p	<0.01	<0.01	<0.01	<0.01	<0.01
	ρ	0.588	0.533	0.640	0.596	0.711
	95% CI	[0.526, 0.643]	[0.391, 0.650]	[0.521, 0.735]	[0.466, 0.700]	[0.609, 0.789]

3.5. User Perception of PM Concentration and Its Misalignment with Measured Levels

In sharp contrast to the concentration and dose patterns, users systematically perceived the “dirtiest” spaces as the cleanest (Figure 7, Table S15). Water spaces were rated as having the lowest PM levels: 94.9% of respondents across the four seasonal campaigns classified air quality there as low or relatively low. Understory spaces were also widely perceived as clean. By contrast, squares received the highest proportion of ratings indicating moderate or worse air quality (26.4%). Overall, respondents perceived lower PM levels in understory and water spaces and higher levels in squares and sports spaces, with perceived PM increasing from spring < summer < autumn < winter.

Open-ended responses revealed four dominant rationales for these judgments. First, overall comfort (47.2%, a composite of thermal, visual, and acoustic impressions) was the most frequently cited basis for ratings, even though respondents often found it difficult to articulate specific cues. Second, vegetation cover (15.6%) was equated with filtration, with many respondents explicitly stating that “more greenery means less dust”. Third, water influence (10.6%) played a role; most respondents believed water bodies reduce PM, although a minority thought polluted water could increase it. Fourth, urban vs.

park context (10.0%) reflected prior beliefs about city-wide pollution and the presumed mitigation role of parks, with 8.1% perceiving PM to be higher in parks because of urban background and 2.2% believing the opposite due to natural features.

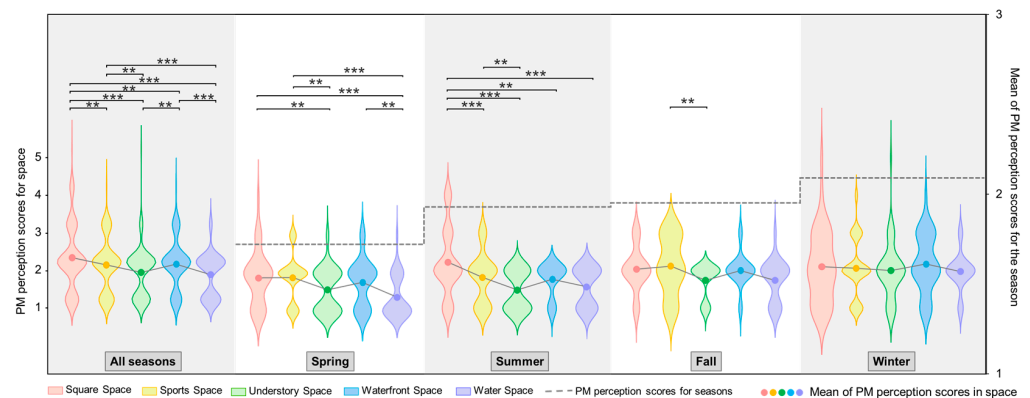


Figure 7. User ratings of perceived PM concentration by space and season. Significance levels: $p < 0.01$ (**), and $p < 0.001$ (***).

Perceptions did not consistently align with measured PM levels. No significant correlation was observed between perception scores and measured PM_1 and $PM_{2.5}$ concentrations, while significant negative correlations emerged for PM_{10} and TSP (Table 3). These correlation results indicate that users tended to rate air quality as better in spaces where coarse-particle concentrations were actually higher. Conceptually, this represents a systematic misalignment: understory and water spaces, which had comparatively high measured PM_{10} /TSP, were typically rated as clean (negative misalignment), whereas squares and, to a lesser extent, sports spaces, which were relatively cleaner in concentration terms, were rated more poorly (positive misalignment).

Table 3. Correlation between measured and perceived PM levels.

	PM_1	$PM_{2.5}$	PM_{10}	TSP
ρ	0.03	−0.02	−0.08	−0.10
p	0.47	0.65	0.02	0.01

Crucially, 78.1% of respondents reported that their choice of activity space was influenced by perceived air quality, meaning that this misalignment is not merely attitudinal but behaviorally consequential. Combined with the crowding-dose associations in Section 3.4, these findings suggest a maladaptive behavioral pattern: users preferentially aggregate in spaces that look and feel clean but in fact deliver higher inhaled PM doses, thereby undermining the potential respiratory-health benefits of parks.

4. Discussion

4.1. A Design-Behavior-Perception-Dose Architecture in Urban Parks

This study shows that urban parks do not offer a uniform “clean-air benefit”; instead, they exhibit a design-driven exposure architecture in which spatial configuration, user behavior, and risk perception jointly organize PM doses. Three findings are central: (1) The most popular spaces were also the highest-dose spaces. Sports and understory areas combined elevated PM concentrations, high-intensity activities or long dwell times, and large user counts, particularly in winter. (2) “Clean-looking” spaces were not necessarily clean: water and understory spaces, which had relatively high PM_{10} and TSP, were systematically perceived as having better air quality than squares and waterfront spaces, which were

often cleaner in concentration terms. (3) Across the four seasonal fair-weather campaigns, space type-behavior combinations were more stable than seasonal variation in background pollution, indicating that design-locked use patterns act as a more persistent organizer of dose than meteorology alone. Together, these patterns confirm that the health implications of parks cannot be inferred from concentration fields alone. Instead, dose emerges from the coupling of micro-environment, behavior, and perception, echoing broader exposure-science arguments that dose is the product of concentration, ventilation, and time and extending them into a fine-grained park design context [4,14].

4.2. Mechanisms: From Micro-Scale Concentration Patterns to Dose Hotspots

Our concentration results are consistent with the increasingly nuanced literature on the air-quality impacts of urban greenery. At city and landscape scales, more vegetation is generally associated with lower $PM_{2.5}$ and improved air quality [26–28]. Yet recent reviews emphasize that at micro-scales, vegetation can either mitigate or intensify particulate pollution depending on structural features and flow regimes [29,30]. Dense tree canopies and shrub belts can suppress vertical mixing, trap coarse particles, and promote resuspension from surfaces, whereas open lawns and well-ventilated waterfronts tend to favor dispersion [31,32]. The persistent ranking we observed (waterfront spaces with the lowest PM_{10} /TSP, understory and water spaces with the highest) fits this micro-scale picture: tree understory and enclosed watersides in our parks behave as low-porosity, low-ventilation compartments, while waterfront promenades and open squares operate as quasi-corridors that can drain polluted air.

However, concentration is only one side of the dose equation. The behavioral data show that park design strongly structures both the intensity and duration of activity, consistent with systematic reviews of behavior in public open spaces [33–35] and SOPARC-based park studies [23,36]. Sports facilities in our parks concentrated MVPA and attracted the longest stays, while understory spaces, offering shade, seating, and a sense of enclosure, encouraged prolonged lower-intensity lingering. Waterfronts and water spaces, by contrast, mainly hosted short, lower-intensity bouts such as walking, strolling, photographing, or brief resting, echoing findings that “water-friendliness” boosts visit frequency but not necessarily high-intensity use [37,38].

When these behavioral portfolios are multiplied by concentrations, sports and understory areas emerge as persistent dose hotspots across seasons. In sports spaces, high-intensity exercise dramatically elevates ventilation rates, thus even moderate PM levels translate into substantial inhaled loads, particularly during winter haze episodes. In understory spaces, high coarse-particle loads combine with long dwell times, yielding high doses despite mostly lower-intensity activities. By contrast, open water spaces achieve both shorter and less intense occupancy; thus, they remain low-dose environments even when background pollution is high. These mechanisms illustrate that park design does more than redistribute pollution; it orchestrates a multi-factor dose mechanism in which structural vegetation, openness, amenity placement, and shading determine where people go, how long they stay, and how hard they breathe.

4.3. Misaligned Perceptions and Maladaptive Space Choices

A striking result is the systematic mismatch between perceived and measured air quality. Understory and water spaces (e.g., our concentration hotspots) were overwhelmingly rated as having low or very low PM, while squares, which were relatively cleaner, attracted more “moderate or poor” ratings. This mirrors wider evidence that people’s perceptions of air pollution often diverge from real-time exposure, influenced by heuristics, media, and local context [17–19]. Mobility-based studies show that individuals frequently

underestimate exposure in familiar or aesthetically pleasing settings and overestimate it in less pleasant but less polluted environments [18,39]. In our parks, respondents reported relying mainly on diffuse comfort cues, such as shade, greenery, water, and overall pleasantness, rather than on any direct sensory markers of particulates. This aligns with studies in which vegetation and “naturalness” are taken as proxies for cleanliness even when PM_{2.5} is high [40]. Water bodies and tree canopies are especially powerful visual and thermal cues: they cool microclimates, soften noise, and visually block urban infrastructure, thereby sending a strong “safe and restorative” signal that can override invisible air-quality risks.

The public-health implications are non-trivial. Perceived air quality is not merely an attitude; it is predictive of protective behavior and sometimes more closely associated with health outcomes than objective pollution metrics [41]. In our sample, over three-quarters of users reported that perceived air quality influenced their choice of activity space. Combined with the observed misalignment, this indicates a maladaptive pattern in which users preferentially aggregate in visually attractive but polluted micro-environments and avoid relatively cleaner but more “exposed” or “urban-feeling” areas such as squares. Similar mismatches between perceived and measured risk have been observed at neighborhood scales, where residents worry most about areas with modest health risks while underestimating far more hazardous locations [42]. Our findings therefore support a more critical view of the assumption that “if people feel a park is healthy, it is healthy.” Instead, perception can actively steer users into high-dose micro-environments, undermining the potential respiratory benefits of park visits even as parks continue to support physical and mental health in other ways.

4.4. Implications for Exposure-Aware Park Design and Management

These results point to several design and management principles for parks in polluted cities. First, high-use, high-dose spaces should be prioritized for mitigation. Sports courts and understory pockets are structural dose hubs, where high concentrations, intense or prolonged activity, and large crowds converge. Locating these spaces as far as feasible from major roads and other emission sources and ensuring they are embedded within well-ventilated park layouts could substantially reduce cumulative doses. At a minimum, high-intensity courts should not be placed downwind of busy roadways or in enclosed “street canyon-park” hybrids where traffic emissions easily spill into the park [30,43].

Second, understory and water spaces should be reconfigured to reduce stagnation and resuspension without sacrificing their restorative qualities. This might involve introducing breaks in dense shrub belts, avoiding continuous, tall hedge “walls” around activity areas, using mixed-height canopies to promote some vertical mixing, and managing ground surfaces to limit dust accumulation. Micro-scale experiments suggest that heterogeneity and porosity in vegetation structure can maintain cooling and aesthetic benefits while preventing the build-up of coarse particles [44,45].

Third, activity programming should be aligned with micro-environmental air quality, not just convenience or aesthetics. Where measurements or models identify relatively clean micro-environments (e.g., ventilated waterfronts or squares), these should be the preferred locations for high-intensity and long-duration activities, especially for vulnerable groups (older adults, patients in rehabilitation). Providing shade, benches, and attractive planting in these cleaner zones can shift the behavioral gravitation towards low-dose environments, building on evidence that specific spatial features (e.g., comfort, accessibility, and supporting facilities) strongly shape MVPA and park use [46,47].

Fourth, air quality should be made more perceivable and actionable. Given that users currently rely on misleading comfort cues, there is scope for low-cost interventions such as real-time park-level PM displays, graded warning flags linked to public monitoring net-

works, or signage that highlights “cleaner routes” and “cleaner spaces” on high-pollution days. These measures could help align intuitive space choices with actual exposure gradients, complementing city-wide strategies that promote active park use. Importantly, such communication should be framed to avoid deterring park use altogether, instead encouraging users to reallocate time and activity within parks towards cleaner micro-environments. Collectively, these principles argue for integrating exposure-aware thinking into park design guidelines, on par with thermal comfort, biodiversity, and accessibility objectives. Together, these strategies contribute to sustainable park planning by aligning environmental risk reduction with the continued provision of recreational, restorative, and social functions. Rather than reducing park use to avoid exposure, exposure-aware design can support healthier and more sustainable outdoor recreation by guiding intensive and long-duration activities toward lower-dose micro-environments.

4.5. Environmental Health Equity: Who Receives Which Doses?

The design-behavior-perception architecture documented here also has implications for environmental health equity. Older adults and people with cardiovascular or respiratory disease are among those most susceptible to PM-related morbidity and mortality [48,49]. Yet these groups often rely heavily on parks for low-cost physical activity and social interaction. If they are disproportionately drawn to shaded understory and sports spaces (precisely the micro-environments that deliver the highest inhaled doses), then parks could inadvertently concentrate risk in the very populations that derive the greatest non-air-quality benefits.

Evidence from multiple countries shows that structural inequalities already shape who is exposed to outdoor air pollution: low-income communities, racialized minorities, and residents of deprived neighborhoods typically face higher PM_{2.5} and NO₂ levels and bear disproportionate cardiovascular and respiratory burdens [50–52]. Environmental health frameworks highlight that such exposures often interact with psychosocial stress and other social determinants to amplify risk [53]. Against this backdrop, poorly aligned park design and perception could create a second layer of inequality within ostensibly “healthy” green infrastructure: those who can and do access parks, and who may already be vulnerable, might receive higher doses than residents who avoid parks or use only cleaner subspaces.

Moreover, climate change is increasing the frequency of heatwaves in many cities, and heat and PM exposures together show supra-additive health impacts, particularly in socioeconomically burdened neighborhoods [54,55]. If the same spaces that offer thermal refuge (dense understory near water) simultaneously deliver high PM doses, then trade-offs between heat relief and air-quality risk need to be made explicit in design decisions. Our findings thus argue for a health-equity lens in park planning, foregrounding the question: who is likely to use which micro-environments, under which pollution and heat conditions, and with what cumulative risk?

4.6. Limitations and Future Directions

Several limitations should be noted when interpreting these findings. First, the study was conducted in a single medium-sized city and focused on five archetypal space types within four parks. While these space types are common in Chinese urban parks, other cities may have different configurations, adjacent emission sources, vegetation structures, or climatic regimes that produce stronger or weaker concentration gradients. In addition, sampling was conducted during daytime periods under generally stable fair-weather conditions and did not cover nighttime periods, post-rainfall conditions, strong-wind events, or severe pollution episodes. Therefore, the findings should be interpreted as multi-season daytime fair-weather exposure patterns rather than continuous year-round exposure estimates. The five-type spatial classification also simplified the complexity of

park micro-environments, as transitional spaces, roadside buffer zones, composite forest-water spaces, and finer design attributes were not explicitly examined. Therefore, the strength and direction of design-dose coupling may vary across more polluted, more enclosed, or more compositionally complex park settings. A finer-grained classification of park spaces across a broader range of urban and climatic contexts is an important direction for future research.

Second, users' perceptions of air quality were measured using brief, cross-sectional Likert scales at the plot level. This approach captures broad tendencies but may underestimate intra-individual variability and the situational nuances of perception [39]. Future work could integrate experience-sampling or mobility-based exposure and perception tracking, as well as qualitative methods, to better understand how people interpret multisensory cues when they move through parks.

Third, inhaled doses were estimated using population-average inhalation rates and short observation windows, which may obscure inter-individual variability. Future assessments could integrate wearable sensors, heart rate monitoring, and GPS tracking to capture dynamic activity and exposure transitions.

Finally, this study focused on conventional particulate indicators and did not measure gaseous pollutants or particle-bound toxic components, such as ozone, volatile organic compounds, or heavy metals. Therefore, the findings reflect PM exposure patterns rather than the full spectrum of respiratory-health risks in park environments.

Despite these constraints, the convergence of concentration, behavior, and perception patterns across multiple seasons and parks suggests that the observed design-behavior-perception-dose couplings are robust within the sampled daytime fair-weather recreational conditions. The limitations mainly define the scope of inference and indicate the need for future work under additional weather, pollution, spatial, and individual-exposure scenarios.

5. Conclusions

This study demonstrates that urban parks embody a design-driven exposure architecture: spatial configuration creates a stable hierarchy of micro-environments in which PM concentrations, behavioral intensity, dwell time, and perceived air quality are jointly organized across seasons. First, PM_{2.5}, PM₁₀, and TSP concentrations were lower in waterfront and square spaces but higher in water and understory spaces, showing that vegetation and water bodies do not necessarily reduce PM concentrations at the micro-environmental scale. Their effects depend on the balance among deposition, dispersion, enclosure, ventilation, and local resuspension. Second, park space design consistently structured user behavior by shaping where people stayed, how long they remained, and what intensity of activity they performed. Sports spaces attracted more vigorous and prolonged activities, whereas understory spaces supported longer stays and lower-intensity leisure activities. Third, when PM concentrations were combined with activity intensity and dwell time, sports and understory spaces emerged as the highest-dose environments, especially under winter haze conditions. These high-dose spaces were also among the most heavily used areas, indicating that elevated exposure coincided with greater user aggregation. Fourth, perceived air quality often diverged from measured PM concentrations. Users frequently relied on visual and environmental cues, particularly vegetation and water features, when judging air quality, which may steer visitors toward spaces that appear clean but deliver higher inhaled PM doses.

These findings imply that maximizing the health benefits of parks in polluted cities requires moving beyond generic "more green" strategies toward exposure-aware design and management. Practical strategies include prioritizing mitigation in high-use, high-dose spaces, improving ventilation and surface management in dense understory and

water-related spaces, reallocating intensive and long-duration activities to cleaner micro-environments, and making air-quality information more legible in situ so that perception and behavior align more closely with actual exposure. In this way, urban parks can better support outdoor recreation, environmental health, and sustainable landscape design while reducing avoidable PM exposure under everyday recreational conditions.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/su18146955/s1>. Supplementary Text S1 and Tables S1–S15 are provided in the attached Supplementary Documents. These materials include space-type selection criteria, plot characteristics, monitoring dates and meteorological conditions, observer-consistency analysis, statistical tests, mixed-effects sensitivity models, meteorological correlations, activity-type summaries, per capita exposure analyses, and perceived air-quality analyses. The detailed information is as follows: Text S1. Selection Criteria for Different Space Types. Table S1. Detailed information on each plot. Table S2. Monitoring time of atmospheric particulate matter concentration and meteorological conditions during monitoring. Table S3. Consistency analysis of observations among different observers at different time periods. Table S4. Results of Kruskal–Wallis tests for PM concentrations across spatial groups. Table S5. Kruskal–Wallis test for pollutants across four seasons. Table S6. Type III ANOVA tests of fixed effects from mixed-effects sensitivity models based on pooled four-season PM concentration data. Table S7. Random-effect variances and model-fit statistics for mixed-effects sensitivity models based on pooled four-season PM concentration data. Table S8. Season-stratified mixed-effects sensitivity models testing spatial differences in PM concentrations. Table S9. Random-effect variance ranges and model-fit statistic ranges for season-stratified mixed-effects sensitivity models. Table S10. Relationships between meteorological factors and atmospheric PM concentrations. Table S11. Typical activity types by space type (ranked by participation). Table S12. Kruskal–Wallis tests for spatial differences in per-capita PM exposure among park space types. Table S13. Sensitivity analysis of the effect of space type on per-capita particulate matter exposure across pooled four-seasona and seasonal datasets. Table S14. Sensitivity analysis of the association between total population and per capita particulate matter exposure. Table S15. Kruskal–Wallis tests for differences in perceived air-quality scores by space type and season.

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References

1. World Health Organization. Ambient (Outdoor) Air Pollution. Available online: <https://www.who.int/news-room/fact-sheets/detail/ambient-%28outdoor%29-air-quality-and-health> (accessed on 24 October 2024).
2. Jiang, Y.; Luo, H.; Fu, G.; Chen, J.; Kan, H.; Chen, R. Global burden of early-onset cardiovascular disease attributable to fine particulate matter pollution from 1990 to 2021: A systematic analysis for the Global Burden of Disease Study 2021. *BMC Med.* **2025**, *23*, 472. [\[CrossRef\]](#)
3. Chowdhury, S.; Pillarisetti, A.; Oberholzer, A.; Jetter, J.; Mitchell, J.; Cappuccilli, E.; Aamaas, B.; Aunan, K.; Pozzer, A.; Alexander, D. A global review of the state of the evidence of household air pollution's contribution to ambient fine particulate matter and their related health impacts. *Environ. Int.* **2023**, *173*, 107835. [\[CrossRef\]](#)
4. National Research Council. *Exposure Science in the 21st Century: A Vision and a Strategy*; The National Academies Press: Washington, DC, USA, 2012.
5. Bray, I.; Reece, R.; Sinnett, D.; Martin, F.; Hayward, R. Exploring the role of exposure to green and blue spaces in preventing anxiety and depression among young people aged 14–24 years living in urban settings: A systematic review and conceptual framework. *Environ. Res.* **2022**, *214*, 114081. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Sugiyama, T.; Carver, A.; Koohsari, M.J.; Veitch, J. Advantages of public green spaces in enhancing population health. *Landsc. Urban Plan.* **2018**, *178*, 12–17. [\[CrossRef\]](#)
7. Abhijith, K.V.; Kumar, P.; Gallagher, J.; McNabola, A.; Baldauf, R.; Pilla, F.; Broderick, B.M.; Di Sabatino, S.; Pulvirenti, B. Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments—A review. *Atmos. Environ.* **2017**, *162*, 71–86.
8. Xing, Y.; Brimblecombe, P. Role of vegetation in deposition and dispersion of air pollution in urban parks. *Atmos. Environ.* **2019**, *201*, 73–83. [\[CrossRef\]](#)
9. Venter, Z.S.; Hassani, A.; Stange, E.; Schneider, P.; Castell, N. Reassessing the role of urban green space in air pollution control. *Proc. Natl. Acad. Sci. USA* **2024**, *121*, e2306200121. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Chen, L.; Zhang, Z.; Long, Y. Association between leisure-time physical activity and the built environment in China: Empirical evidence from an accelerometer and GPS-based fitness app. *PLoS ONE* **2021**, *16*, e0260570. [\[PubMed\]](#)
11. Sallis, J.F.; Cerin, E.; Kerr, J.; Adams, M.A.; Sugiyama, T.; Christiansen, L.B.; Schipperijn, J.; Davey, R.; Salvo, D.; Frank, L.D.; et al. Built environment, physical activity, and obesity: Findings from the International Physical Activity and Environment Network (IPEN) Adult Study. *Annu. Rev. Public Health* **2020**, *41*, 119–139. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Song, Y.; Newman, G.; Huang, X.; Ye, X. Factors influencing long-term city park visitations for mid-sized US cities: A big data study using smartphone user mobility. *Sustain. Cities Soc.* **2022**, *80*, 103815.
13. Zhai, Y.; Li, D.; Wu, C.; Wu, H. Spatial distribution, activity zone preference, and activity intensity of senior park users in a metropolitan area. *Urban For. Urban Green.* **2023**, *79*, 127761. [\[CrossRef\]](#)
14. U.S. Environmental Protection Agency. *Guidelines for Human Exposure Assessment*; Risk Assessment Forum, U.S. Environmental Protection Agency: Washington, DC, USA, 2019.
15. Giallourou, G.; Kouis, P.; Papatheodorou, S.I.; Woodcock, J.; Tainio, M. The long-term impact of restricting cycling and walking during high air pollution days on all-cause mortality: Health impact assessment study. *Environ. Int.* **2020**, *140*, 105679. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Sun, Q.; Yang, C.; Jiang, M.; Yang, M.; Mao, M.; Fan, Z. Ambient air pollution does not diminish the beneficial effects of active commuting on heart failure: A prospective study in UK Biobank. *BMC Public Health* **2025**, *25*, 828. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Hong, W.; Wei, Y.; Wang, S. Left behind in perception of air pollution? A hidden form of spatial injustice in China. *Environ. Plan. C Politics Space* **2022**, *40*, 666–684.
18. Song, W.; Kwan, M.-P.; Huang, J. Assessment of air pollution and air quality perception mismatch using mobility-based real-time exposure. *PLoS ONE* **2024**, *19*, e0294605. [\[PubMed\]](#)
19. Aswin Giri, J.; Shiva Nagendra, S.M. Air pollution perception for air quality management: A systematic review exploring research themes and future perspectives. *Environ. Res. Lett.* **2024**, *19*, 053002. [\[CrossRef\]](#)
20. Ryu, Y.-H.; Min, S.-K. What matters in public perception and awareness of air quality? Quantitative assessment using internet search volume data. *Environ. Res. Lett.* **2020**, *15*, 0940b4.21. [\[CrossRef\]](#)
21. Lindberg, M.; Schipperijn, J. Active use of urban park facilities—Expectations versus reality. *Urban For. Urban Green.* **2015**, *14*, 909–918.
22. McKenzie, T.L.; Cohen, D.A.; Sehgal, A.; Williamson, S.; Golinelli, D. System for Observing Play and Recreation in Communities (SOPARC): Reliability and Feasibility Measures. *J. Phys. Act. Health* **2006**, *3*, S208–S222. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Evenson, K.R.; Jones, S.A.; Holliday, K.M.; Cohen, D.A.; McKenzie, T.L. Park characteristics, use, and physical activity: A review of studies using SOPARC (System for Observing Play and Recreation in Communities). *Prev. Med.* **2016**, *86*, 153–166. [\[CrossRef\]](#) [\[PubMed\]](#)

24. Ministry of Environmental Protection of the People's Republic of China. *Exposure Factors Handbook of Chinese Population (Adults)*; China Environmental Science Press: Beijing, China, 2013.
25. U.S. Environmental Protection Agency. *Exposure Factors Handbook: 2011 Edition (Final Report)*; EPA/600/R-09/052F; U.S. Environmental Protection Agency: Washington, DC, USA, 2011.
26. Lei, Y.; Davies, G.M.; Jin, H.; Tian, G.; Kim, G. Scale-dependent effects of urban greenspace on particulate matter air pollution. *Urban For. Urban Green.* **2021**, *61*, 127089. [[CrossRef](#)]
27. Han, L.; Zhang, R.; Wang, J.; Cao, S.-J. Spatial synergistic effect of urban green space ecosystem on air pollution and heat island effect. *Urban Clim.* **2024**, *55*, 101940. [[CrossRef](#)]
28. Zhai, C.; Bao, G.; Zhang, D.; Sha, Y. Urban forest locations and patch characteristics regulate PM_{2.5} mitigation capacity. *Forests* **2022**, *13*, 1408. [[CrossRef](#)]
29. Xing, Y.; Brimblecombe, P.; Wang, S.; Zhang, H. Tree distribution, morphology and modelled air pollution in urban parks of Hong Kong. *J. Environ. Manag.* **2019**, *248*, 109304. [[CrossRef](#)]
30. Tomson, M.; Kumar, P.; Barwise, Y.; Perez, P.; Forehead, H.; French, K.; Morawska, L.; Watts, J.F. Green infrastructure for air quality improvement in street canyons. *Environ. Int.* **2021**, *146*, 106288. [[CrossRef](#)] [[PubMed](#)]
31. Pace, R.; Guidolotti, G.; Baldacchini, C.; Pallozzi, E.; Grote, R.; Nowak, D.J.; Calfapietra, C. Comparing i-Tree Eco estimates of particulate matter deposition with leaf and canopy measurements in an urban Mediterranean Holm oak forest. *Environ. Sci. Technol.* **2021**, *55*, 6613–6622. [[CrossRef](#)] [[PubMed](#)]
32. Gao, T.; Liu, F.; Wang, Y.; Mu, S.; Qiu, L. Reduction of atmospheric suspended particulate matter concentration and influencing factors of green space in urban forest park. *Forests* **2020**, *11*, 950. [[CrossRef](#)]
33. Ward Thompson, C. Activity, exercise and the planning and design of outdoor spaces. *J. Environ. Psychol.* **2013**, *34*, 79–96. [[CrossRef](#)]
34. Koohsari, M.J.; Mavoa, S.; Villanueva, K.; Sugiyama, T.; Badland, H.; Kaczynski, A.T.; Owen, N.; Giles-Corti, B. Public open space, physical activity, urban design and public health: Concepts, methods and research agenda. *Health Place* **2015**, *33*, 75–82. [[CrossRef](#)] [[PubMed](#)]
35. Fan, Z.; Lv, Y.; Guo, L. Research on the impact of the urban park built environment on physical activity. *Sci. Rep.* **2025**, *15*, 28586. [[CrossRef](#)] [[PubMed](#)]
36. Liu, M.; Chen, C.; Yan, J. Identifying park spatial characteristics that encourage moderate-to-vigorous physical activity among park visitors. *Land* **2023**, *12*, 717.
37. Bao, Y.; Gao, M.; Luo, D.; Zhou, X. Urban parks—A catalyst for activities! The effect of the perceived characteristics of the urban park environment on children's physical activity levels. *Forests* **2023**, *14*, 423.
38. Nelson, J.R.; Won, Y.; Kim, J.E.; Stuhlmacher, M.; Kim, Y. Is the grass greener or the water bluer? Drivers of local park visitation patterns in Phoenix, Arizona. *Urban For. Urban Green.* **2024**, *95*, 128325. [[CrossRef](#)]
39. Song, W.; Kwan, M.-P. Air pollution perception bias: Mismatch between air pollution exposure and perception of air quality in real-time contexts. *Health Place* **2023**, *84*, 103129. [[CrossRef](#)] [[PubMed](#)]
40. Yang, B.; Chen, Y. PM_{2.5} pollutant concentrations in greenspaces of Nanjing are high but can be lowered with environmental planning. *Int. J. Environ. Res. Public Health* **2021**, *18*, 9705. [[CrossRef](#)] [[PubMed](#)]
41. Huang, Y.-J.; Lee, P.-H.; Hsieh, S.-H.; Chiu, Y.-C.; Chan, T.-C. Understanding factors influencing adoption of air pollution protective measures using the knowledge-attitude-behavior model. *Sci. Rep.* **2024**, *14*, 28414. [[PubMed](#)]
42. Noël, C.; Vanroelen, C.; Gadeyne, S. Qualitative research about public health risk perceptions on ambient air pollution. A review study. *SSM Popul. Health* **2021**, *15*, 100879. [[CrossRef](#)] [[PubMed](#)]
43. Huang, Y.; Lei, C.; Liu, C.-H.; Perez, P.; Forehead, H.; Kong, S.; Zhou, J.L. A review of strategies for mitigating roadside air pollution in urban street canyons. *Environ. Pollut.* **2021**, *280*, 116971. [[CrossRef](#)] [[PubMed](#)]
44. Yu, M.; Mi, X.; Li, Y.; Jiang, C.; Ding, K.; Wang, C.; Cai, L. Exploring the potential mechanisms of urban greenspaces providing pollution retention and cooling benefits based on three-dimensional structure of plant communities. *Sci. Rep.* **2024**, *14*, 28410. [[CrossRef](#)] [[PubMed](#)]
45. Barwise, Y.; Kumar, P. Designing vegetation barriers for urban air pollution abatement: A practical review for appropriate plant species selection. *NPJ Clim. Atmos. Sci.* **2020**, *3*, 12. [[CrossRef](#)]
46. Levinger, P.; Dreher, B.L.; Soh, S.E.; Dow, B.; Batchelor, F.; Hill, K.D. Results from the ENJOY MAP for HEALTH: A quasi experiment evaluating the impact of age-friendly outdoor exercise equipment to increase older people's park visitations and physical activity. *BMC Public Health* **2024**, *24*, 1663. [[PubMed](#)]
47. Veitch, J.; Rodwell, L.; Abbott, G.; Carver, A.; Flowers, E.; Crawford, D. Are park availability and satisfaction with neighbourhood parks associated with physical activity and time spent outdoors? *BMC Public Health* **2021**, *21*, 306. [[CrossRef](#)] [[PubMed](#)]
48. Wu, X.; Braun, D.; Schwartz, J.; Kioumourtzoglou, M.-A.; Dominici, F. Evaluating the impact of long-term exposure to fine particulate matter on mortality among the elderly. *Sci. Adv.* **2020**, *6*, eaba5692. [[CrossRef](#)] [[PubMed](#)]

49. Sun, Y.; Milando, C.W.; Spangler, K.R.; Wei, Y.; Schwartz, J.; Dominici, F.; Nori-Sarma, A.; Sun, S.; Wellenius, G.A. Short term exposure to low level ambient fine particulate matter and natural cause, cardiovascular, and respiratory morbidity among US adults with health insurance: Case time series study. *BMJ* **2024**, *384*, e076322. [[CrossRef](#)] [[PubMed](#)]
50. Rentschler, J.; Leonova, N. Global air pollution exposure and poverty. *Nat. Commun.* **2023**, *14*, 4432. [[CrossRef](#)] [[PubMed](#)]
51. Tessum, C.W.; Paoletta, D.A.; Chambliss, S.E.; Apte, J.S.; Hill, J.D.; Marshall, J.D. PM2.5 polluters disproportionately and systemically affect people of color in the United States. *Sci. Adv.* **2021**, *7*, eabf4491. [[PubMed](#)]
52. Jbaily, A.; Zhou, X.; Liu, J.; Lee, T.-H.; Kamareddine, L.; Verguet, S.; Dominici, F. Air pollution exposure disparities across US population and income groups. *Nature* **2022**, *601*, 228–233. [[CrossRef](#)] [[PubMed](#)]
53. Clougherty, J.E. Invited perspective: Temporality and recursive dynamics in stress–pollution interactions. *Environ. Health Perspect.* **2022**, *130*, 121302. [[CrossRef](#)] [[PubMed](#)]
54. Chen, C.; Schwarz, L.; Rosenthal, N.; Marlier, M.E.; Benmarhnia, T. Exploring spatial heterogeneity in synergistic effects of compound climate hazards: Extreme heat and wildfire smoke on cardiorespiratory hospitalizations in California. *Sci. Adv.* **2024**, *10*, eadj7264. [[CrossRef](#)] [[PubMed](#)]
55. Hsu, A.; Sheriff, G.; Chakraborty, T.; Many, D. Disproportionate exposure to urban heat island intensity across major US cities. *Nat. Commun.* **2021**, *12*, 2721. [[CrossRef](#)] [[PubMed](#)]

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